# Machine-Learning Applications in Ports Electrification – A Rapid Review

Luis Nunes
*ITI/LARSyS*
*Técnico Lisboa, University of Lisbon*
Lisbon, Portugal
luis.goncalves.nunes@tecnico.ulisboa.pt

Fábio Mendonça
*ITI/LARSyS*
*University of Madeira*
Funchal, Portugal
fabioruben@staff.uma.pt

Lucas Pereira
*ITI/LARSyS*
*Técnico Lisboa, University of Lisbon*
Lisbon, Portugal
lucas.pereira@tecnico.ulisboa.pt

***Abstract*—Ports are essential to global trade and logistics, but they face substantial challenges in aligning with sustainability goals, particularly in reducing greenhouse gas emissions and improving energy efficiency. Machine-Learning (ML) has emerged as a tool to address these challenges by enabling more accurate predictions of energy demand and optimization of port operations. This paper provides a rapid review of ML applications within port operations, focusing specifically on energy efficiency. The review examines three key areas, namely, ship energy consumption, the energy demands of cruise ships, and the implementation of shore-side electricity. Therefore, this work analyzes the current state of ML applications in these areas to identify challenges and opportunities, including the lack of publicly available data and the absence of established performance benchmarks, which hinder the widespread adoption of ML-driven solutions for enhancing sustainability in port operations.**

***Index Terms*—Energy Efficiency, Energy Consumption, Shore Side Electricity, Machine Learning in Ports, Forecasting**

## I. Introduction

The maritime sector is a major contributor to Global Greenhouse Gas (GHG) emissions, responsible for about 2.5% of the total. This industry is, however, essential for global trade despite the dependence on fossil fuels, such as heavy fuel oil and marine diesel, which harm the environment. Reducing emissions from this sector is thus necessary to address climate change. This is further supported by international agreements like the Paris Agreement, and the International Maritime Organization's decarbonization goals highlight the need for cleaner and more efficient solutions [1], [2]. These steps are needed for reducing greenhouse gas emissions, promoting sustainability, and ensuring compliance with evolving regulations [3], while also meeting the demands of stricter environmental standards [4].

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In recent years, researchers have been exploring new technologies and strategies to reduce emissions in maritime transport. Tools enabled by Machine-Learning (ML) and big data analytics are being used to improve energy efficiency by analyzing factors such as weather conditions, ship design, and how vessels operate [5]. At the same time, alternative fuels like Liquefied Natural Gas (LNG), hydrogen, ammonia, and biofuels are being studied. However, these options face challenges such as the need for expensive infrastructure, safety concerns, and questions about affordability [6], [7].

Renewable energy sources like wind and solar (PV) are also being considered, especially in ports and auxiliary ship systems. However, scaling these solutions to meet the larger energy demands of the industry is difficult, mainly due to issues with reliability and cost [8]. While governments and organizations are offering financial incentives and creating new regulations to support decarbonization, these efforts often don't fully address the unique energy needs of the maritime sector.

One of the most promising ways to lower emissions is through electrification. This includes using technologies like batteries, hybrid systems, and shore-side electricity (also known as cold ironing), which allow ships to rely less on fossil fuels and operate more efficiently [9], [10]. However, electrification comes with its challenges. These include the need for substantial investments in infrastructure, upgrades to port electrical grids, and the creation of strong regulatory systems to ensure success [11].

Given the rapid advancements in port electrification and the growing relevance of ML, a focused literature review is necessary to assess the current state of research, identify key challenges, and highlight emerging opportunities. To the authors' knowledge, no comprehensive review currently consolidates these developments, particularly in ML applications for energy optimization in ports.

This paper is organized as follows. Section II presents the foundational aspects of port and maritime operations.Section III examines the role of electrification in decarbonizing port systems.Section IV reviews the state-of-the-art applications of ML in the maritime sector, with emphasis on optimizing energy consumption in ships, cruise liners, and port operations. The paper concludes in Section V with a summary of the main challenges and research opportunities for achieving a sustainable energy transition in the maritime industry.

## II. Overview of the Ports Industry

Ports are vital hubs in the global supply chain and critical drivers of economic activity, facilitating the transfer of goods and passengers between maritime transport and other modes of transportation [12]. They support international trade, enable industrial growth, and generate significant employment opportunities in surrounding regions [13]. Different types of ports cater to specific economic and logistical needs, specifically: (i) Commercial Ports: Handle diverse cargo, including containers, bulk solids, and liquids, using specialized equipment like cranes and advanced storage systems to ensure efficient operations; (ii) Industrial Ports: Support heavy industries by transporting raw materials and finished goods with infrastructure adapted for large-scale bulk operations; (iii) Fishing Ports: Focus on unloading, processing, and storing fishery products with refrigeration and specialized facilities to maintain freshness and quality [14]; (iv) Tourist Ports: Serve cruise ships and recreational vessels, offering tourism and commercial services that drive local economic growth [15].

Port operations, including cargo handling, container cooling, and crane operations, require careful management to ensure efficiency and minimize delays caused by weather, congestion, and unforeseen circumstances.

## III. Electrification in Ports

Port electrification is a solution to reduce reliance on fossil fuels and cut GHG emissions by transitioning systems to electric operations powered by the grid and renewable energy. However, successful implementation necessitates robust infrastructure, including:(i) Charging Stations for Ships: Shore-side electricity enables ships to use port electrical grids (instead of onboard fossil fuel generators), substantially reducing emissions during docking [16], and, in this regard, optimization methods, such as mixed-integer linear programming models, demonstrate how strategic allocation of chargers can lower energy costs and enhance operational efficiency [17]; (ii) Upgraded Electrical Grid: Ports need to upgrade their electrical infrastructure to support electrification, including enhanced substations and energy management systems [18], for instance, the Port of Aalborg's hybrid microgrid integrated PV and wind power, achieving an 85.3% renewable fraction and reducing emissions by over 80%, while also generating economic savings through energy sales [19]; (iii) Integration of Renewable Energy: As per point (ii), ports can adopt PV, wind, and wave energy systems to cut emissions and reduce operational costs [20].

A successful example is the Port of Naples, where a renewable energy hub combining various technologies significantly lowered emissions and achieved payback periods of 4 to 14 years, demonstrating both economic and environmental benefits [21].

This alternative to traditional energy sources offers substantial opportunities, such as emission reductions and improved operational efficiency, but also presents notable challenges [22]. High initial infrastructure investment is one of the primary obstacles [23], requiring careful planning to address factors such as charging station location, electrical grid capacity, and coordination with ship operations. Despite these challenges, several ports have already started implementing electrification technologies with promising results. For instance, the Port of Los Angeles has developed an extensive "shore power" infrastructure, enabling ships to shut down their auxiliary engines while docked, which significantly reduces emissions of particulates and nitrogen oxides [24].

## IV. State-of-the-Art Analysis

The articles analyzed in this review were selected through a structured search on the ScienceDirect database, using the following search phrases: "shore-side electricity"; "cold ironing"; and "energy efficiency in ports". This was complemented by a snowball strategy, where references from the most relevant papers were used to identify additional studies. A total of 14 articles were then analyzed, with publication year distribution: 2015 (1); 2018 (2); 2020 (4); 2022 (1); 2023 (3); 2024 (3).

This section is structured based on insights derived from a bibliometric analysis using *VOSviewer* Fig. 1, which visualizes key research topics and their interconnections in maritime energy optimization. The clusters identified in the analysis reflect the main focus areas in current research, allowing for a structured examination of the literature. As represented in Fig. 1, the map highlights three major clusters: (i) Energy Efficiency and Ship Energy Consumption: This theme centers on strategies to enhance operational efficiency and reduce emissions across maritime activities, addressing the increasing need for fuel optimization and environmental responsibility; (ii) Cruise Ship Energy Demands: Given their distinctive operational profiles and complex energy requirements, cruise ships present dissimilar challenges that require specialized solutions for energy optimization, and, research in this cluster focuses on balancing propulsion with non-propulsion energy needs to achieve sustainable operations; (iii) Cold Ironing: As docked vessels can connect to renewable energy sources onshore, this methodology reduces the need for onboard generators.

To provide further detail, the word cloud, presented in Fig. 2, of the examined articles was produced, highlighting the most prominent terms in maritime energy optimization literature. Larger words like *energy*, *ship*, *consumption*, *system*, and *port* indicate topics of high frequency. Furthermore, this visualization captures the central themes, such as *cold ironing*, *renewable energy*, and *efficiency*, as well as analytical approaches like *machine learning* and *model*.

### A. Ships Energy Consumption

Accurate energy consumption forecasting is required for optimizing fuel efficiency and improving operations, thus reducing emissions in the maritime sector. This task is influenced by factors like ship design, operational parameters, and environmental conditions.

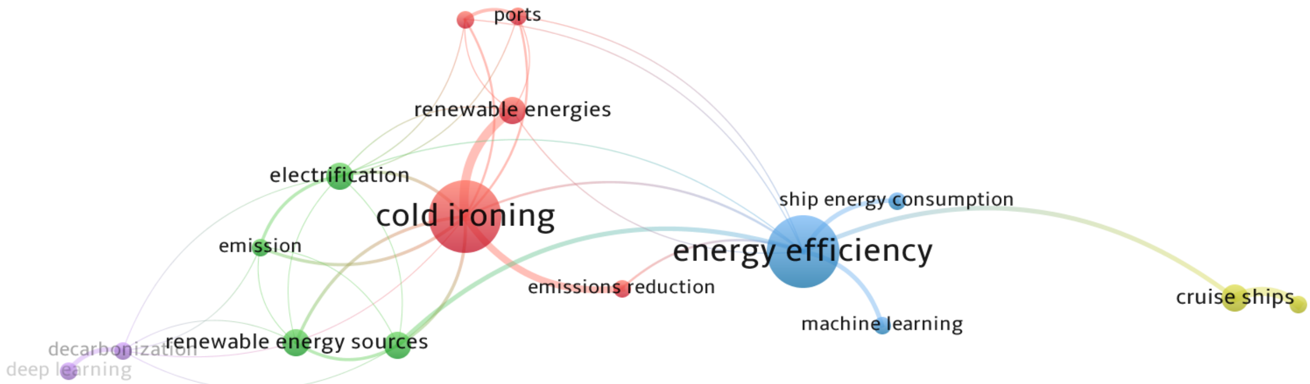


Fig. 1. Network visualization obtained from VOSviewer of key research themes related to maritime energy optimization based on bibliometric analysis.

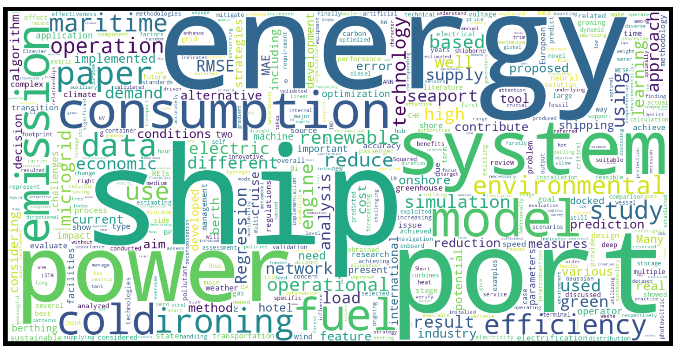


Fig. 2. Visualization of the frequently used keywords in maritime energy optimization studies.

Boertz et al. [25] addressed the challenge of predicting energy consumption by developing dynamic ML models that adapt in real-time to various operational factors. The study was capable of improving energy consumption forecasts by using techniques like Gaussian Process Regression (GPR) and Support Vector Machines (SVM), enabling better decision-making for fuel efficiency and performance optimization. The models were developed using data from the Automatic Identification System (AIS), five Typical Days of Operation (TDO), International Organization for Standardization (ISO) regulations, and the Holtrop and Mennen method.

Peng et al. [26] used ML to predict energy consumption for ships in JingTang Port, China, addressing challenges posed by varying operational and environmental conditions. Their study aimed to support green port initiatives by improving energy consumption forecasting. The dataset, collected by JingTang Port, included data from 8,019 ships. Although actual energy consumption data was unavailable, the paper used mathematical equations to estimate the energy consumption of ships in port. Techniques like Decision Trees (DT) and Random Forests were employed to develop predictive models tailored to port operations, promoting sustainable maritime practices.

Shu et al. [27] developed an energy consumption model by using neural networks to capture complex energy patterns under various operational scenarios, enhancing prediction accuracy and operational efficiency. Their study focused on trip data from the Pearl River Delta, processed through advanced neural network architectures involving Physics-Informed Neural Networks (PI-NNs), Recurrent Neural Networks (RNNs), Deep Neural Networks (DNNs), and Long Short-Term Memory (LSTM) networks, providing insights for ports and shipping companies to meet environmental regulations while maintaining high operational standards. The data were sourced from 40 round-trip voyages of a trailing suction hopper dredger in the Pearl River Delta.

Uyanik et al. [28] and Zhang et al. [29] also applied various ML models to predict energy consumption across different types of vessels, addressing the challenge of developing models capable of handling diverse operational profiles. Uyanik et al. used standard Artificial Neural Networks (ANN) and Multiple Linear Regression (MLR) to estimate power and fuel consumption, while Zhang et al. employed techniques such as Adaptive Boosting (AB) and LSTM to manage large, complex datasets, resulting in more accurate predictions of energy consumption. Both studies utilized datasets from specific vessels, but these datasets were not made publicly available.

Yuan and Nian [30] proposed a Gaussian Process (GP) metamodel for predicting ship energy consumption, using its flexibility to model complex non-linear relationships. Their study emphasized the importance of incorporating uncertainty quantification for better risk management and decision-making in energy planning, creating robust tools for forecasting energy needs and optimizing operational efficiency in maritime transportation.

Collectively, the reviewed literature demonstrates a methodological progression from conventional statistical approaches such as MLR and traditional GP models towards more complex models, encompassing ensemble methods including DT and Random Forests, advanced ANN paradigms such as PI-NNs, RNNs, DNNs, and LSTM networks, alongside hybrid techniques including GPR, SVM, and AB, thereby establishing a comprehensive taxonomic spectrum of computational models ranging from elementary parametric formulations to complex non-linear architectures for maritime energy consumption prediction.

### B. Cruise Ships Energy Consumption

Cruise ships, with their unique energy demands, require specialized energy optimization strategies. These vessels must manage propulsion energy and hotel loads such as lighting, heating, and other amenities. Strategies include improving hull design, optimizing propulsion systems, implementing slow steaming, optimizing routes, and efficiently managing loads [31]. Furthermore, technologies such as energy-efficient lighting, efficient systems for Heating, Ventilation, and Air Conditioning (HVAC), and waste heat recovery are increasingly utilized to reduce energy consumption, with smart energy management systems playing a crucial role in monitoring and optimizing energy use [32].

Micallef et al. [33] developed a two-stage approach combining constraint-based algorithms with GP Regression (GPR) to estimate non-propulsive energy demands of cruise ships, such as lighting and heating. The models incorporated engine power and propulsion constraints for improved accuracy, supporting energy management in the cruise industry. The data used came from the private Valletta Cruise Port database, which included 412 port calls and 89 unique ships between January 2022 and July 2023. They also used classification societies (DNV, RINA, Lloyds Register, and Bureau Veritas) and maritime analytics providers to validate certain vessel data.

Barri et al. [34] explored energy management in cruise ships using ML techniques, such as DTs and K-Nearest Neighbors (K-NN). Their research aimed to optimize energy use under varying operational conditions and the complex energy demands of cruise ships. They demonstrated the potential of smart systems in improving energy efficiency, particularly through real-time data analytics that identify inefficiencies and optimize energy use. The study utilized a large database, built from thousands of files, incorporating studies on energy consumption in buildings and 250 data samples from four transatlantic cruises over one month.

The examined methodological framework reveals a progressive enhancement in computational complexity from elementary distance-metric formulations to more complex probabilistic models with incorporated domain-specific constraints for cruise ship energy consumption forecasting.

### C. Shore-Side Electricity

Shore-side Electricity provides economic advantages by lowering ship operational costs and supporting efficient port operations. Additionally, it has proven to improve air quality in port cities, benefiting public health and the quality of life for residents [35] [36].

Rolan et al. [37] proposed a cold ironing system for the Port of Barcelona, designed to integrate renewable energy sources such as wind and solar power to meet 100% of the energy demands for the cold ironing process. The system includes an offshore wind farm and a PV plant, along with the necessary infrastructure for power conversion and adaptation to meet the specific requirements of berthed vessels. Simulation results demonstrate promising system stability and effectiveness in reducing greenhouse gas emissions. The authors based their analysis on confidential data provided by the Authority of the Port of Barcelona, supplemented by the Port of Barcelona traffic statistics and data from Marine Traffic.

Lamprinidi et al. [38] also studied the financial viability of combining cold ironing with a PV system at the Thessaloniki Port, considering different ship types like bulk carriers, container ships, and cruise ships. They used data on solar radiation, temperature, wind speed, and ship energy demands from the port authorities. The results showed that the PV system improved financial viability in scenarios with mixed ship types and high daytime energy demand, but in cases with only bulk carriers, costs were too high, requiring subsidies.

These works demonstrate the application of simulation-based methodologies and techno-economic feasibility analyses in evaluating renewable energy integration strategies for shore-side electricity systems, establishing a foundational framework for sustainable port electrification initiatives.

## V. Challenges and Opportunities

The state-of-the-art analysis highlights several challenges in applying ML to port electrification, particularly in energy consumption forecasting. One major challenge is the lack of standardized, high-quality datasets, as seen in [25], [26], which rely on proprietary or estimated data. This restricts the generalizability of ML models, leading to performance variations across different vessel types and operational conditions. Additionally, models such as those developed by Shu et al. [27] and Zhang et al. [29] require extensive computational resources, making real-time deployment challenging.

Another challenge is the lack of standardized benchmarking methodologies, including widely accepted performance metrics and evaluation tools. Many studies develop models using different datasets and preprocessing techniques, making direct comparisons difficult, and performance evaluation is often limited to conventional error metrics such as Mean Absolute Error (MAE) or Root Mean Square Error (RMSE), as seen in the works of Zhang et al. [29] and Shu et al. [27]. More comprehensive evaluation frameworks, integrating uncertainty quantification and real-world validation, are thus needed to ensure practical applicability, similar to what has been achieved in other ML fields, e.g., [39], [40].

Despite these challenges, there are opportunities to improve ML-based maritime energy forecasting. Hybrid models that combine physics-based approaches with ML, such as those by Yuan and Nian [30], could improve performance while maintaining interpretability. Looking ahead, advancements in distributed optimization and transfer learning could help overcome data scarcity and computational limitations.

Additionally, developing open-access maritime datasets, as suggested by Uyanik et al. [28], would enhance model training and validation, promoting more robust and transferable ML solutions. Future research should prioritize the development of robust benchmarking frameworks, fostering collaboration among researchers, industry stakeholders, and policymakers. This would not only improve the credibility of ML-driven energy optimization solutions but also accelerate their adoption in real-world maritime settings.

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